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PREDICTIONS OF THE AIRBLAST AND GROUND MOTIONS RESULTING FROM EXPLOSIVE REMOVAL OF THE BIRDS POINT-NEW MADRID FUZE PLUG LEVEE

by

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Emergency flood procedures call for the creation of two large crevasses in the Birds Point-New Madrid fuze plug levee on the Mississippi River below Cairo, Ill.

Slurry explosives will be used to create 11,400- and 6000-ft breaches in the levee system. Potential hazards to nearby structures from airblast and ground shock from these explosions (128 and 67 tons, respectively) were assessed.

(Continued)

20. ABSTRACT (Continued)

Conventional methods could not be used to predict explosion effects because of (a) the unusual geometry of the explosion and (b) most civil blasting safety procedures were developed for rock. A data base from row charge experiments in soil was analyzed for this project.

As a result of this study, it is believed that:

a. No structural damage should be expected at distances greater than 1800 ft from either levee section.

b. An isolated ejecta clod is possible but not probable at distances of 2500 ft.

c. Safe limits will be the same for both crevasses, depending only on the linear loading density of the explosive (lb/ft of levee).

d. Although residents of Wickliffe, Ky., may hear the airblast and feel the ground vibrations, no window or structural damage should be expected there.

e. Cairo, Ill., will not be affected. No complaints are anticipated.

PREFACE

This report presents an assessment of the airblast and ground motion hazards for explosively creating breaches in the Birds Point-New Madrid fuze plug levee on the Mississippi River below Cairo, Illinois. This assessment was conducted for the Memphis District, CE, under Intra-Army Order 81-22 dated 2 July 1981.

Messrs. Jim Drake and Leo Ingram of the Explosion Effects Division of the Structures Laboratory conducted the study and authored this report.

CONTENTS

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	2.54	centimetres
feet	0.3048	metres
pounds (force per square inch	6.894757	kilopascals
pounds (force per square inch	69.0	mbar
inches per second	2.54	centimetres per second
pounds (mass)	0.4535924	kilograms
miles	1.609344	kilometres

PREDICTIONS OF THE AIRBLAST AND GROUND MOTIONS RESULTING FROM EXPLOSIVE REMOVAL OF THE BIRDS POINT-NEW MADRID FUZE PLUG LEVEE

PART I: INTRODUCTION

Background

1. The December 1979 draft of the Emergency Operations Plan (EOP) (Reference 1) describes in detail the procedure for explosively creating breaches in the Birds Point-New Madrid fuze plug levee on the Mississippi River below Cairo, Illinois. Creation of two large crevasses would use an estimated 128 and 67 tons of explosive slurry along 11,400- and 6,000-ft sections of the levee system, respectively. Airblast and ground motions produced by the detonation of large quantities of explosives pose a potential hazard to nearby structures. The objective of this report is to assess these hazards and to estimate distances from the explosions where no appreciable damage would be expected.

Problem Statement

2. The EOP describes in detail the operations including explosive amounts and configurations to be used to create the crevasses. Briefly, two crevasses are planned: No. 1 is 11,400 ft long and No. 2 is 6,000 ft long. The explosive plan is nearly the same for each crevasse--three parallel lines of explosive charges spaced 12 ft apart, running the length of each crevasse. Holes containing 120 lb of aluminized slurry explosive will be placed at 16-ft intervals along each line, providing about 22.5 lb of explosive per lineal foot of crevasse. Thus, approximately 128 tons of slurry will be used on Crevasse No. 1 and about 67 tons is planned for Crevasse No. 2. Demolition of the crevasses will not be simultaneous.

3. Initiation of individual charges will be by explosive detonation cord (trade named Primacord). The Primacord will be placed in a loop above the ground to provide redundancy in the initiation chain. Because the Primacord detonates at a velocity of about 22,000 ft/sec, it

will take approximately one-half second to detonate the entire 11,400-ft row of charges in Crevasse No. 1. There will be no deliberate attempt to delay detonation of the individual charges. The area surrounding the levee system is sparsely populated farmland within the floodway to the southwest (See Figure 1). The nearest population center of concern is Wickliffe, Kentucky, which is located across the Mississippi River northeast of Crevasse No. 1 at a distance of about 8700 ft. Cairo, Illinois, is located about three miles north of Crevasse No. 1 and should not be affected by the explosion.

Approach

4. Because of the complexity of the explosive source--multiple charges in a row with non-simultaneous detonations--there are no known methods to calculate the long range blast and shock effects from first principle approaches. Therefore, our approach is to use data collected on past explosion tests--both single burst and row charge events--scaled to fit this situation. In most cases, upper bounds of these data were used to provide conservative estimates of the potential hazards.

5. The problem of detonating nearly simultaneous row charges in very large quantities in soil is unusual to both civil construction and industrial applications. Most civil blasting is in rock such as mining, quarry operations, or construction excavation and is normally detonated in delayed sequences to reduce the ground shock vibrations. For rock blasting a large body of literature is devoted to blasting safety and the development of criteria for blasting damage to structures. No literature was found for civil blasting applications in soils.

6. A data base for buried explosions in soil had to be developed for the current problem to provide estimates of the airblast and ground shock hazard. Most large scale buried bursts in soil are from Department of Defense simulations of the effects of buried nuclear explosions. Principal sources of single burst data include the ESSEX* and Diamond Ore series of 10-ton to 40-ton explosions in soil and shale, respectively. Ground motions from row charges were assessed from the MEACE**

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* Effects of Subsurface Explosives

** Military Engineering Application of Commercial Explosives

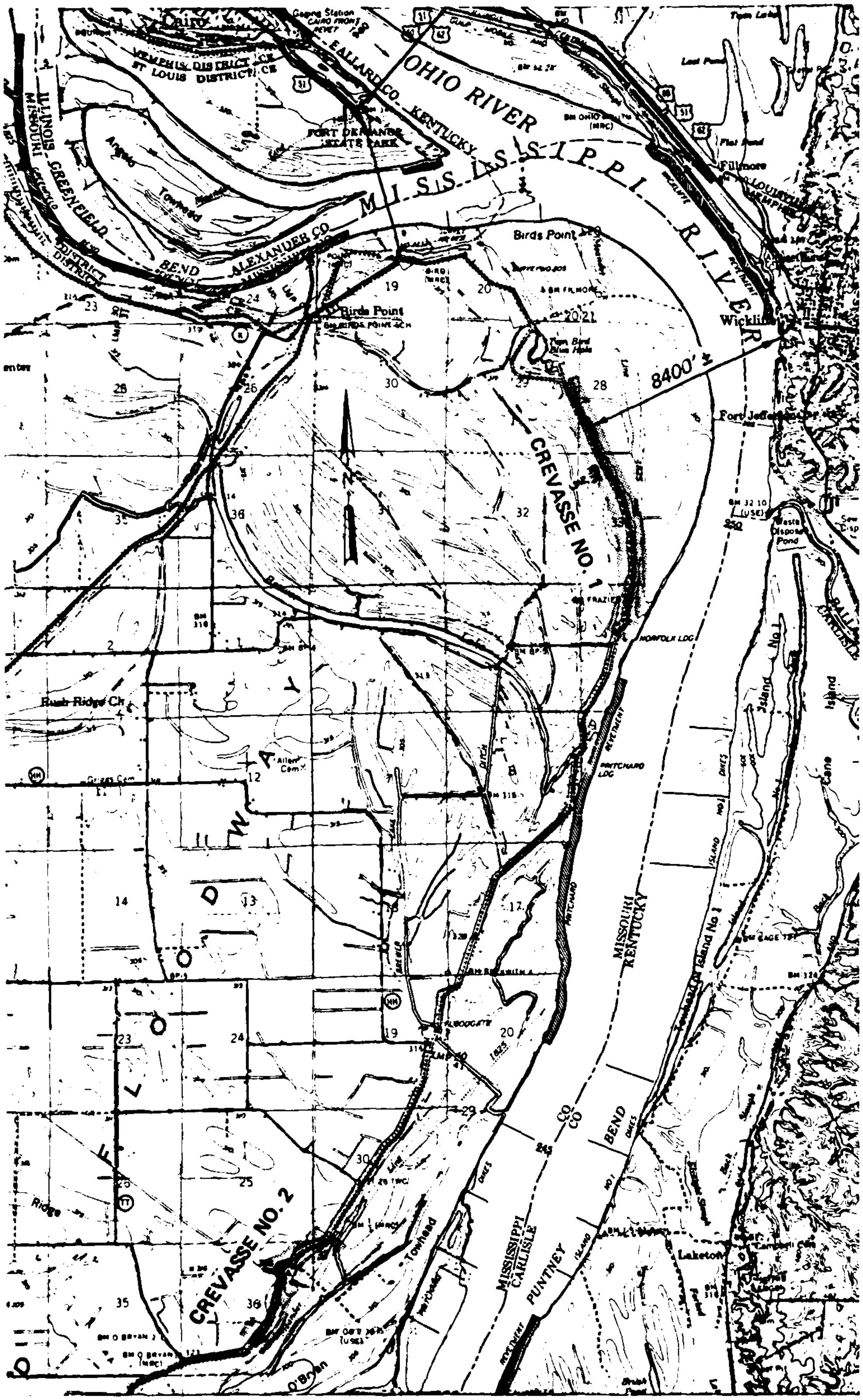


Figure 1. Vicinity map, Birds Point - New Madrid Floodway.

and related row cratering experiments; the airblast from buried row charges was developed from Plowshare test data.

7. Factors that influence the strength of airblast and ground shock from buried cratering row charges include: soil properties (primarily saturation) depth-of-burial, degree of stemming, local geology and geometric relationships of the target point to the charge.

a. Soil Properties. In general peak particle velocity (a damage index) is lower for explosions in soil than in rock. Wet soils can produce high accelerations and generally exhibit higher particle velocities. Vibration periods of ground motions in soils are much lower than in rock, thus resulting in larger particle displacements near the charge. Ground motion frequencies are typically proportional to the shear wave velocity in the geologic medium.

b. Depth-of-Burial. Ground shock increases rapidly with increase in depth of burial until the explosion is near optimum depth of burst for cratering where it becomes essentially fully tamped. Airblast is quickly suppressed by increasing depth of burial. Shallow bursts produce a strong gas-venting airblast wave. Deeper bursts produce an airblast pulse from sudden upward movement of the ground and a later pulse from venting of the explosion products. For optimum cratering depths, these pulses are of comparable amplitude.

c. Stemming. The degree of stemming (or backfill) strongly influences the airblast produced by the venting explosion products. Ground shock is not strongly affected by stemming for cratering bursts.

d. Local Geology. Strong geologic interfaces between the explosion source and the structure influence the frequency of the ground motion. Shallow depths to rock will produce higher frequency motions, while deep rock layers will result in low frequency particle motions.

e. Charge Geometry. Geometrical spreading of the blast wave and ground motion accounts for much of the attenuation of these effects at increasing distances from the explosion.

(1) Line Charge. Energy from a line charge is distributed initially on the surface of a cylinder. For this case, the energy must be expressed as the charge weight per unit length, w, of the line. Thus, near a long row charge (within one charge length), the amplitude of the airblast and ground motion depends on the linear charge density, w, and not the

total charge weight. In this region, attenuation of effects is much less rapid than for point source explosions and should scale proportional to $(w)^{1/2}$.

(2) Concentrated Charge. Energy from a concentrated burst is distributed initially on the surface of a sphere. At distances greater than the length of a line charge, propagation becomes more and more spherical and the total charge we.?ht, W , must be used to evaluate the potential hazards. Effects in this region scale proportional to $(W)^{1/3}$.

8. For our problem, the population center of Wickliffe, Kentucky, is near the transition point from the cylindrical to spherical propagation region. The available data were separated into these regions and both methods were applied to provide bounds on the resulting effects.

PART II: EXPLOSION HAZARDS

Airblast Hazards

9. Windows are more susceptible to damage from airblast than other structural components; hence we will base our airblast damage criterion on them. Because of the differences in the strength of the glass, window size, frame and glazing conditions, etc., it is impossible to determine a single damage threshold pressure level for all windows. The orientation of the window with respect to the explosion also has a significant effect.

10. Reed (Reference 2) has conducted extensive analyses of airblast propagation and window damage from both controlled explosive tests and accidental explosions. Figure 2, adapted from Reed, shows the probability of window damage based on controlled tests by the Pittsburgh Plate Glass Company and from an accidental explosion near Medina, TX. Reed considers 0.06 psi as the threshold for breaking very large windows with long duration blast waves (from nuclear tests in Nevada). This produces a probability of damage of 3×10^{-5}. The U.S. Bureau of Mines (Reference 5) indicates that a blast pressure level of 0.5 psi is acceptable on windows. The probability of damage at this level is 6 out of 100 windows. While we consider Reed's threshold to be conservative, we believe the risk associated with the U.S. Bureau of Mines threshold to be excessive. If we could predict blast pressure levels with little uncertainty, we would opt for a damage probabality of one in one thousand; this occurs at a pressure level of about 0.145 psi. Since atmospheric conditions (notably unfavorable winds and temperature inversions) can increase blast propagation markedly; these are unpredictable. Thus, it is recommended that Reed's threshold (0.06 psi) be used as the design upper limit of exposure for this operation.

Ground Shock Hazards

11. Rational damage criteria for blasting vibrations cannot be defined by a single measure of ground motion. Several factors influence the response of structures and their susceptibility to damage including type of construction, number of stories, soil and foundation conditions

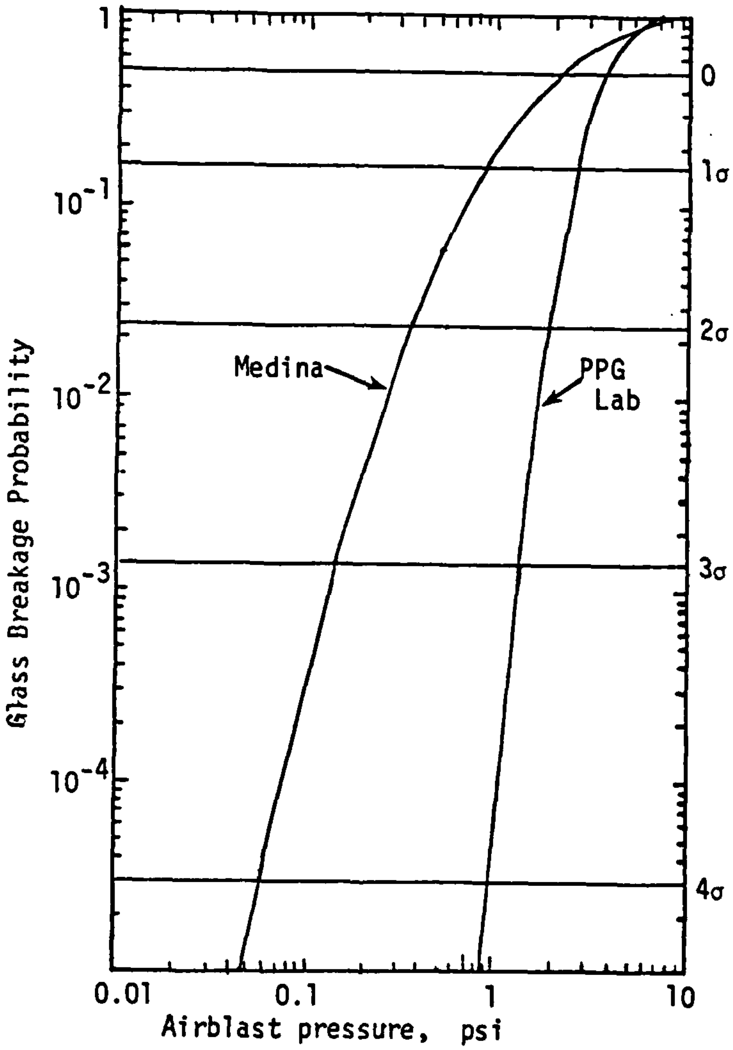


Figure 2. Lognormal probabilities of glass breakage versus applied pressure (after Reed, Reference 2)

and age of the structure, to name only a few. Acceptable damage may also depend on the use of the structure, i.e., motions that crack plaster in a residence may be acceptable for commercial buildings with suspended ceilings. Most complaints associated with blasting involve relatively minor items such as hairline cracks in masonry walls, stucco, gypsum wallboard, plaster, and occasional window breakage. Failure or even potential failure of the primary structure is usually not a problem.

12. In 1949, Crandell (Reference 3) first suggested a measure for safe blasting levels. He found that the energy ratio (ER), defined as the square of the ratio of maximum acceleration in feet per second squared to frequency in Hertz, could be correlated with damage. In a study of over 1000 structures, he found that an ER of 3 or below was safe, and that the danger of producing damage was high for an ER of 6 or greater. For harmonic motion, an ER of 3 to 6 corresponds to maximum particle velocities of 3.3 to 4.7 in./sec, respectively. Other studies have led to similar conclusions.

13. Several states have adopted or are adopting a maximum peak particle velocity such as 2 in./sec as a legal damage criterion. A peak particle velocity maximum of 2 in./sec has been adopted by the Corps of Engineers (Reference 4), throughout the blasting industry, government and in the literature (References 5 thru 7) as the de facto threshold damage criterion, and is therefore used for this study.

14. One aspect that should not be overlooked is the human response to the blast-induced vibrations. Hendron (Reference 7) points out that people can notice transient motions as low as 0.06 in./sec. Motions can become disturbing at 0.4 in./sec, much less than levels that could cause damage to structures. If the explosion is accompanied by an audible airblast, the loud noise is sufficient to prove severity and cause complaints, even at low particle velocity levels of 0.2 in./sec. Figure 3 is a simplified guideline for human response to blasting vibrations.

Ejecta Hazard

15. A large amount of soil will be blown from the vicinity of the explosion to form the crater for the crevasse. Most of this material

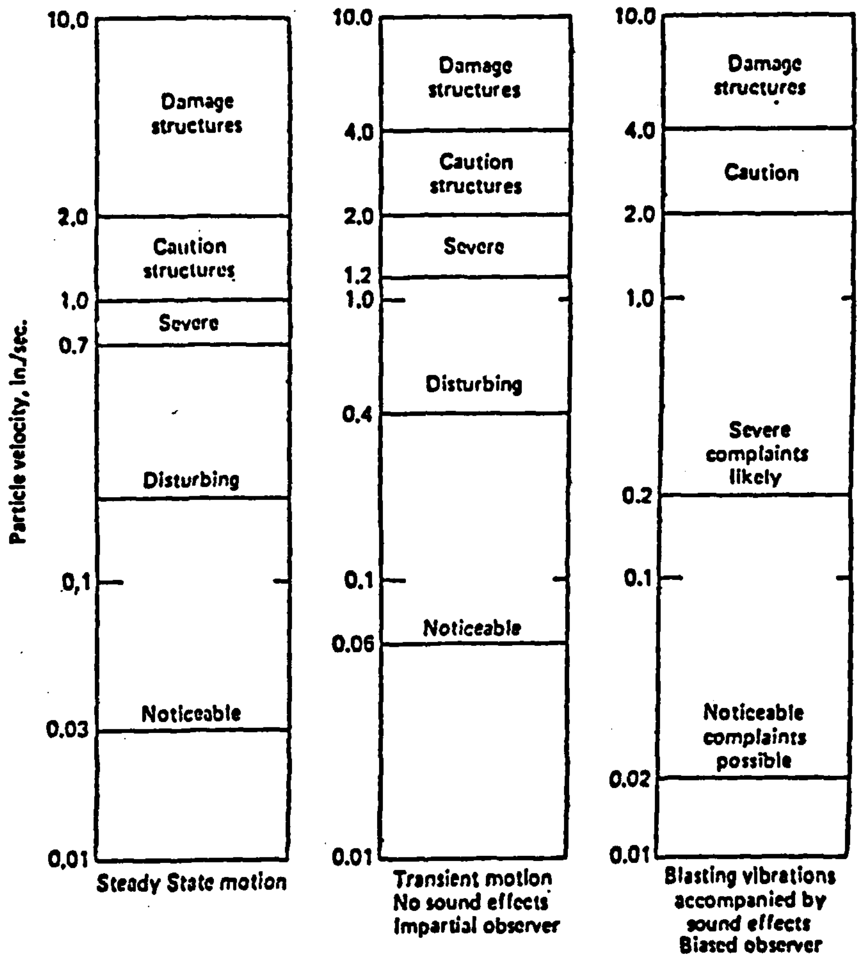


Figure 3. Human response to vibrations (after Hendron, Reference 7).

will fall back into a region within a few crater radii from the line of detonation. The areal density of this material decreases rapidly with increasing distance from the explosion. However, some soil clods may be ejected to considerable ranges from the explosion and could pose a hazard to personal safety.

16. Limited data obtained recently on antitank ditching demonstrations conducted by WES may be used to estimate this hazard. These tests indicate that some ejecta may travel as far as 1500 ft with a very low probability that a clod may extend to 2300 ft for the loading densities considered in this study. While the probability that a given area will experience ejecta clods is remote at these ranges, some ejecta within 1500 and 2500 ft from the explosion is possible.

PART III: EXPLOSION EFFECTS ESTIMATES

General

17. Peak ground motions and airblast estimates are developed in this section from empirical data collected from buried single charge explosions and from limited testing of row charge explosions in soil. Because the crevasses are extremely long, the safe zone for structures will lie in the cylindrical propagation region of the explosion. Thus, estimates for safe limits of airblast and ground motion will depend on the linear loading density and will not be dependent on the length of the crevasse or the total charge detonated.

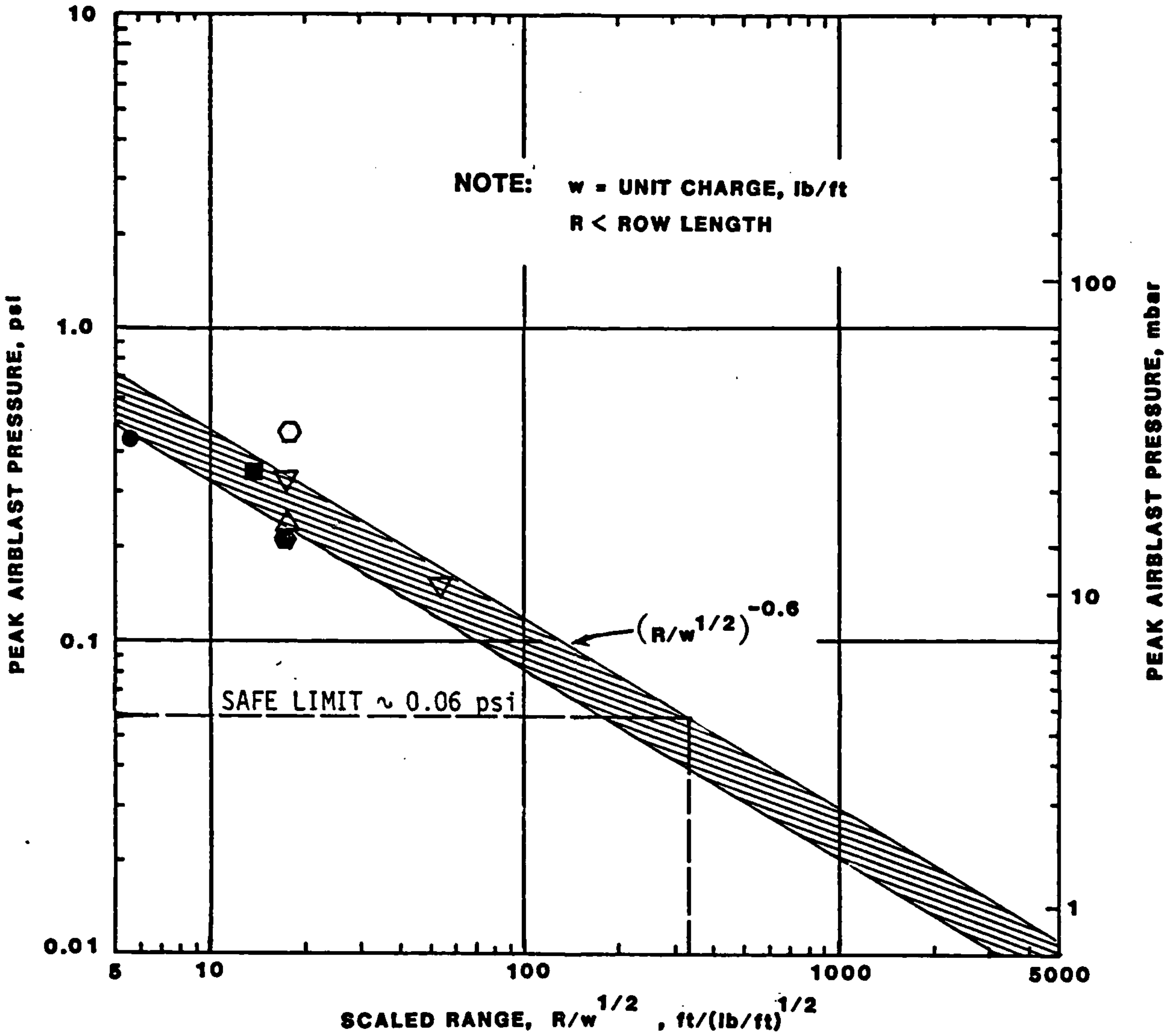
Airblast Effects

18. The data base for airblast from buried line charges is limited to testing conducted in the 1960's for the Plowshare Program by Sandia Laboratories (as reported by Vortman (Reference 8)). In these tests, 64-lb buried charges were detonated at 6.0- and 6.9-ft depth of burial in rows of 2 to 25 charges. Airblast was determined at several ranges from the explosion, both axially and perpendicular to the row. Very few airblast stations were positioned within the cylindrical wave region. These data are presented in Figure 4 where the range is scaled by the square root of the linear explosive mass density. Data in the spherical wave region, i.e., at distances greater than the row length, are presented in Figure 5 where the range is scaled by the cube root of the total charge mass.

19. Because of the limited data in the cylindrical region of interest, an upper bound curve was extrapolated at an attenuation of the -0.6 power of the range. This exponent (-0.6) was chosen to be half of the attenuation noted in the spherical region of -1.2 power of the range--the factor of one-half can be justified by theoretical considerations based on the geometry of the wave divergence.

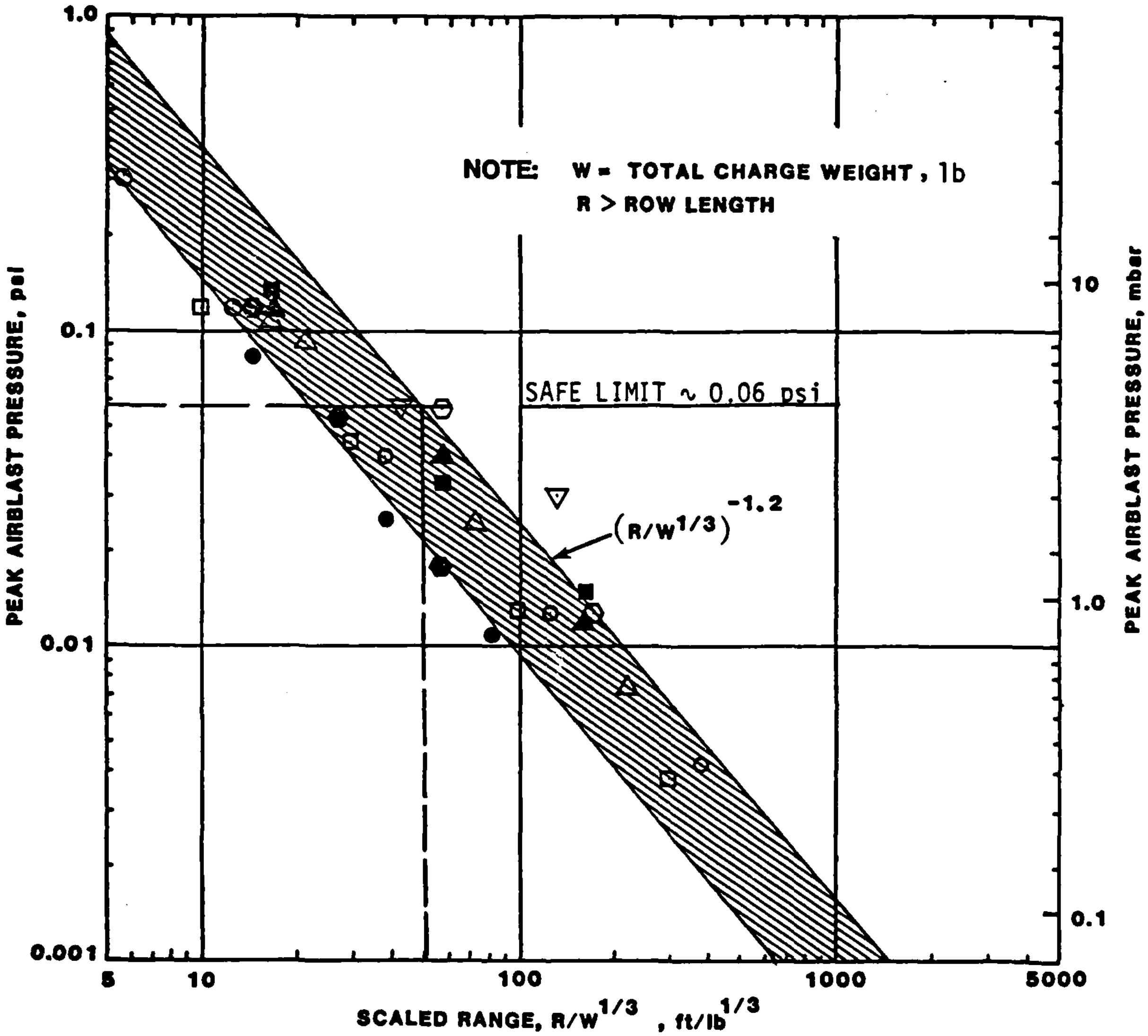
20. Based on this extrapolation, a "safe" limit of 0.06 psi is expected at a scaled range of

$$R/w^{1/2} \sim 325 \text{ ft}/(\text{lb/ft})^{1/2}$$



Symbol	Number of Charges	Mass of Charges (lbs)	Depth of Burst (ft)	Total Charge Mass, W (lbs)	Charge Mass Per Unit Length of row, w (lb/ft)
○	1	64	6.0	64	-
□	2	64	6.0	120	8
△	5	64	6.0	320	8
⬡	11	64	6.0	704	8
▽	25	64	6.0	1600	8
●	5	64	6.9	320	12.2
■	11	64	6.9	704	12.2
▲	1	700	13.0	700	-
⬢	5	256	13.6	1280	18.8

Figure 4. Airblast pressure from row charges scaled (square-root) as a line or cylindrical charge



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□	2	64	6.0	120	8
△	5	64	6.0	320	8
⬡	11	64	6.0	704	8
▽	25	64	6.0	1600	8
●	5	64	6.9	320	12.2
■	11	64	6.9	704	12.2
▲	1	700	13.0	700	-
⬢	5	256	13.6	1280	18.8

Figure 5. Peak airblast pressure from buried single and buried row charges

Thus for linear charge density w of 22.5 lb/ft, a distance of

$$R = 325 \times (22.5)^{1/2} = 1540 \text{ ft, say } 1600 \text{ ft}$$

should be safe for airblast damage to windows for either crevasse. This distance should be considered as the closest distance to the levee.

21. An extremely conservative estimate can be made by lumping all explosives into a single point charge W and using Figure 5 to estimate a safe distance. This approach will give a scaled range of

$$R/W^{1/3} \sim 50 \text{ ft}/(\text{lb})^{1/3}$$

Then for Crevasse No. 1

$$R \sim 50 \times (256{,}000)^{1/3} = 3175 \text{ ft}$$

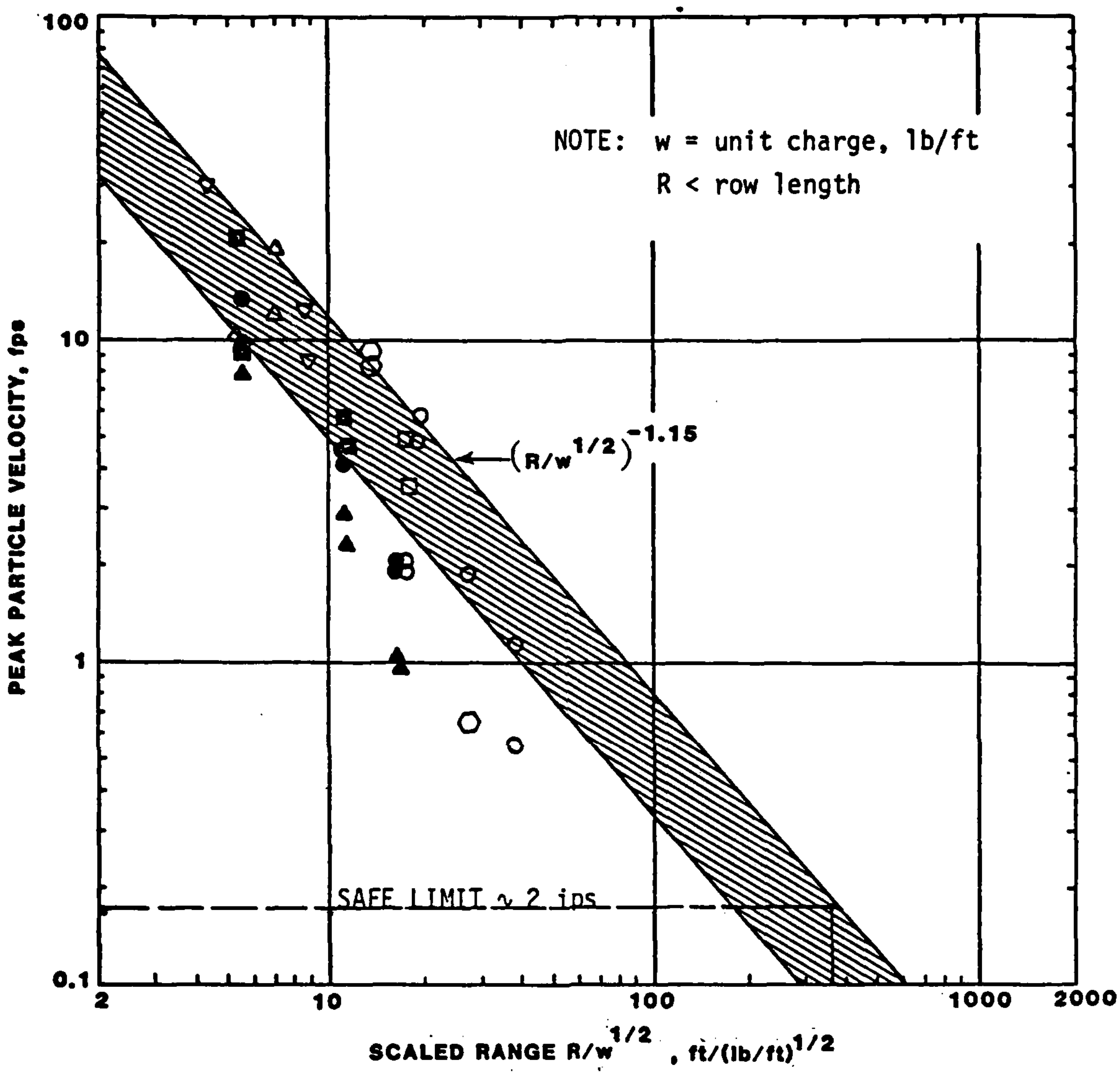
while for Crevasse No. 2

$$R \sim 50 \times (135{,}000)^{1/3} = 2560 \text{ ft}$$

Ground Motions

22. Ground motion data from row charges in soil is limited to testing conducted by WES for the MEACE program and row charge tests at the WES Big Black Test Site. These data are unpublished (Reference 9). Briefly, ground motions were measured axially and along the perpendicular bisector to the row. The number of charges varied from 6 to 12 and the spacing and depth of burst were also varied. Linear charge densities varied from 4 to 18 lb/ft.

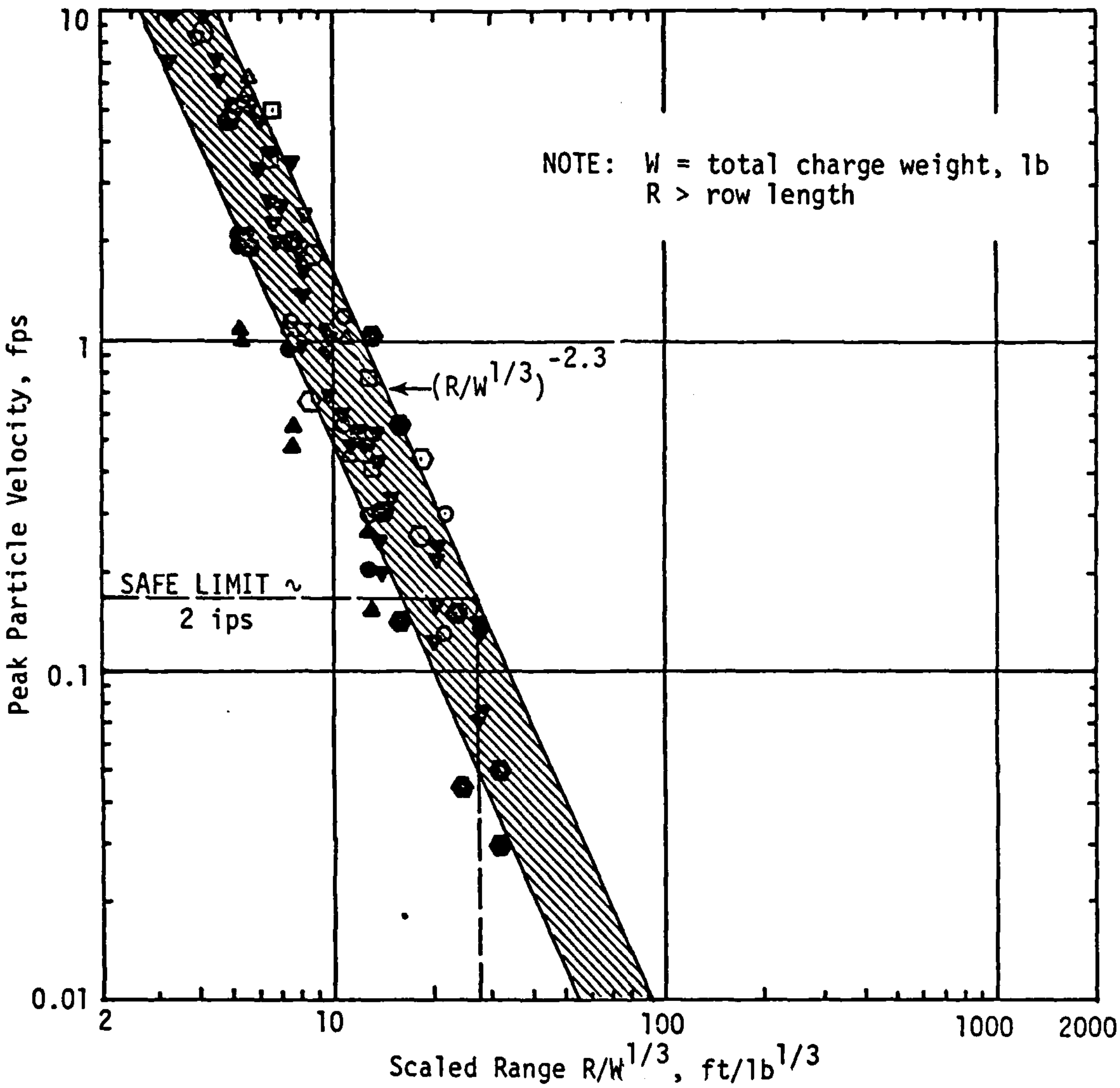
23. Unfortunately, only a few of the measurements fell within the cylindrical wave region. Peak particle velocity data in the region less than the length of the row are shown in Figure 6 plotted versus the range scaled as the square root of the linear charge density. An upper bound curve was fitted with an attenuation with range to the -1.15 power (again half of the spherical wave coefficient). Data within the spherical region are shown in Figure 7, where the peak particle velocity is plotted versus the range scaled to the cube root of the total charge mass.



Symbol	Number of Charges	Mass of Charges (lbs)	Depth of Burst (ft)	Total Charge Mass, W (lbs)	Charge Mass Per Unit Length of row, w (lb/ft)
○	6	60	6.5	360	4.0
□	8	60	9.4	480	8.2
△	10	60	11.1	600	11.3
⬡	10	60	8.5	600	7.4
▽	12	60	10.8	720	18.0
●	5	170	8.5	850	12.8
■	5*	170	8.5	850 (1700)	12.8
▲	5*	170	5.5	850 (1700)	12.8
⬢	1	60	5.5	60	-
▼	1	52	5.5	72	-

* double row, 5 charges each at 40-foot separation

Figure 6. Peak particle motion from row charges scaled (square-root) as a line or cylindrical charge



Symbol	Number of Charges	Mass of Charges (lbs)	Depth of Burst (ft)	Total Charge Mass, W (lbs)	Charge Mass Per Unit Length of row, w (lb/ft)
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△	10	60	11.1	600	11.3
⬡	10	60	8.5	600	7.4
▽	12	60	10.8	720	18.0
●	5	170	8.5	850	12.8
■	5*	170	8.5	850 (1700)	12.8
▲	5*	170	5.5	850 (1700)	12.8
⬢	1	60	5.5	60	-
▼	1	52	5.5	72	-

* double row, 5 charges each at 40-foot separation

Figure 7. Peak particle motion from buried single and buried row charges

24. Based on Figure 6, the safe limit of blasting vibrations of 2 in./sec is expected at a scaled range of about

$$R \times w^{1/2} = 375 \text{ ft/(lb/ft)}^{1/2}$$

Then for both crevasses, a safe distance from the leeve for ground motion is

$$R = 375 \times (22.5)^{1/2} = 1780 \text{ ft, say } 1800 \text{ ft}$$

which is the same distance as for airblast safety.

25. An extremely conservative safe distance can be estimated by considering the total explosion to be concentrated in a single charge. For this case a scaled range of

$$R/W^{1/3} = 28 \text{ ft/(lb)}^{1/3}$$

can be found from Figure 7 to give a 2-in./sec peak particle velocity in the spherical region.

Then for Crevasse No. 1,

$$R = 28 \times (256{,}000)^{1/3} = 1780 \text{ ft}$$

while Crevasse No. 2,

$$R = 28 \times (135{,}000)^{1/3} = 1440 \text{ ft}$$

Ejecta

26. Limited ejecta measurements from row charges would place the limit of the ejecta to be about 1500 ft with a very small probability of a clod extending to 2500 ft.

PART IV: SUMMARY AND CONCLUSIONS

Limits of Damage to Structures

27. Reasonable estimates for safe distances from long row cratering charges are summarized as follows:

Parameter	Safety Criterion	Distance from Crevasse (ft)
Airblast	<0.06 psi	>1600
Ground Motion	<2 in./sec	>1800
Ejecta	Limit of likely ejecta	>1500
	Extreme limit	>2500

Thus, no window breakage or structural damage would be expected at distances greater than 1800 ft from either fuze plug section. An isolated ejecta clod is possible but not probable to distances of 2500 ft. The "safe distance" for the close-in region is independent of the length of the section of leeve to be cratered.

Effects at Wickliffe, Kentucky

28. Wickliffe, Kentucky, situated at least 8,700 ft from Crevasse No. 2, is the closest major center of population to the fuze plug sections. Its scaled distance, considering a line charge, is

$$R/w^{1/2} = 8700\ \mathrm{ft}/(22.5)^{1/2} = 1840\ \mathrm{ft}/(\mathrm{lb/ft})^{1/2}$$

The peak airblast estimated from Figure 4 is 0.02 psi and the maximum particle velocity from Figure 6 is 0.35 in./sec.

29. Airblast is audible at amplitudes as low as 0.002 psi and can be considered loud and noticeable at 0.02 psi. Ground motion can be noticed by humans at 0.06 in./sec and may be disturbing (but not harmful) at 0.4 in./sec.

Effects at Cairo, Illinois

30. Cairo, Illinois, is located about 3 miles north of Crevasse No. 1. Airblast and ground motions can be estimated from Figures 5 and

7 because Cairo is in the spherical propagation region. Thus, the scaled distance is

$$R/W^{1/3} = \frac{16,000 \text{ ft}}{(256,000 \text{ lb})^{1/3}} \sim 250 \text{ ft/lb}^{1/3}$$

At this range the airblast is estimated to be 0.008 psi (barely audible). The predicted peak particle velocity is 0.001 in./sec which is below the level of human perception.

Conclusions

31. Structures should be safe beyond 1800 ft from either explosion. Ejecta clods are possible but extremely unlikely to 2500 ft and should pose no significant hazard to structures.

32. Safe limits will be the same for both crevasses. The limits are dependent only upon the linear loading density and not on the total charge mass detonated.

33. Wickliffe, Kentucky, will be safe. However, the explosion will be perceptible. Ground motions could be felt by humans and may be disturbing, but not harmful. Loose windows and doors may rattle, causing the explosion to be judged as severe by some residents in the area. Some complaints may be possible.

34. Cairo, Illinois, will not be affected by either explosion. It is likely that residents of Cairo will not hear or feel the explosion from Crevasse No. 1. No complaints are anticipated.

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In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Drake, James L.
  Predictions of the airblast and ground motions resulting from explosive removal of the Birds Point-New Madrid fuze plug levee / by James L. Drake, Leo F. Ingram (Structures Laboratory, U.S. Army Engineer Waterways Experiment Station). -- Vicksburg, Miss. : The Station ; Springfield, Va. : available from NTIS, 1981.
  23 p. : ill. ; 27 cm. -- (Miscellaneous paper / U.S. Army Engineer Waterways Experiment Station ; SL-81-30)
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